

Electro-optical measurements of ultrashort 45 MeV electron beam bunch

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We have made an observation of 45 MeV electron beam bunches using the nondestructive electro-optical (EO) technique. The amplitude of the EO modulation was found to increase linearly with electron beam charge and decrease inversely with the optical beam path distance from the electron beam. The risetime of the signal was bandwidth limited by our detection system to ~ 70 ps. An EO signal due to ionization caused by the electrons traversing the EO crystal was also observed. The EO technique may be ideal for the measurement of bunch structure with femtosecond resolution of relativistic charged particle beam bunches.

1. Introduction

Since the first EO observation¹ of charge particle beam we have constructed an optical probe based on the electro-optical Pockels effect. That is, when an electric field is applied to a birefringent crystal an optical phase shift is introduced between orthogonal components. To probe it, a laser beam polarized at 45° to the z-axis of the EO crystal is propagated along the y-axis of the crystal. This phase retardation is converted to an intensity modulation by a $\frac{\lambda}{4}$ plate followed by an analyzer. The intensity of light $I(t)$ exiting the analyzer can be described by²

$$I(t) = I_o[\eta + \sin^2(\Gamma_o + \Gamma_b + \Gamma(t))], \quad (1)$$

where I_o is the input light intensity, η the imperfection of crystal, polarizer and other optics, Γ_o is the crystal residual birefringence, Γ_b is the optical bias of the system which is set at $\frac{\pi}{4}$, and $\Gamma(t)$ is the phase induced by the electric field on the crystal. For a weak modulation, $\Gamma(t) \ll 1$, the EO component can be written as

$$[\frac{I(t)}{I_o}]_{\text{EO}} \sim \Gamma(t) = \frac{1}{2}(n_e^3 r_{33} - n_o^3 r_{13}) \frac{2\pi L E_z(t)}{\lambda} \quad (2)$$

The optical phase shift $\Gamma(t)$ is linearly proportional to the time-dependent field $E_z(t)$ induced by the passage of the electron beam, with $L = \Delta t \times \frac{c}{n} \simeq \frac{r}{\gamma n}$ the distance light travels inside the crystal in the presence of $E_z(t)$, n_e and n_o the extraordinary and ordinary indices of refraction and r_{33} , r_{13} the EO coefficients.

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A relativistic beam produces an anisotropically directed radial field nearly orthogonal to the beam direction and along the z-axis of the EO crystal with strength³

$$E_z(t) = \frac{1}{4\pi\epsilon_0} \frac{\gamma N_e q T(t)}{\epsilon r^2} \quad (3)$$

where γ is the Lorentz factor, N_e the number of electrons in the beam, q the electron charge, $T(t)$ the temporal charge distribution, ϵ_0 the permittivity of free space, ϵ the dielectric constant of the EO crystal in the z-axis direction, and r the radial distance of the electron beam from the axis of the optical beam. Finally

$$\left[\frac{I(t)}{I_o} \right]_{\text{EO}} \simeq (n_e^3 r_{33} - n_o^3 r_{13}) \frac{N_e q T(t)}{4 \lambda n \epsilon_0 \epsilon r} \quad (4)$$

2. Experiment

A vacuum compatible EO modulator setup was constructed using discrete optical components. A Nd:YAG laser, emitting 250 mW of CW power at 1.3 μm was coupled to a vacuum sealed polarization maintaining fiber collimator and the output was rotated +45° to the azimuthal. The collimated 0.4 mm diameter light beam, with polarization purity of $\sim 10^{-2}$, was directed to the LiNbO₃ crystal mounted on a ceramic holder that has a clearance hole of 6.35 mm for the electron beam. The size of the crystal was 6.5(L) x 2.2(H) x 1(W) mm; the optical z-axis was aligned azimuthally and the x-axis was parallel to the propagation direction of the e⁻ beam. Fluorescent material was placed on the ceramic for guiding the e⁻ beam through the EO crystal. A CCD camera and a 45° pop-up flag were also used for electron beam measurements. The electron beam contained up to 0.6 nC charge with beam diameter of ~ 0.5 mm in 10 ps bunch length at a repetition rate of 1.5 Hz.

A vacuum sealed multimode fiber collimator collected the light output from the analyzer and was coupled separately to 1, 12 GHz photodiode which were connected to digitizing oscilloscopes with bandwidth 1, 7GHz.

3. Results

The electron beam induced EO signal origin was confirmed: (1) The signal vanished in the absence of electron or laser beam (2) The signal polarity changed sign when the direction of the electrical field was reversed (by placing the e⁻ beam above and below the crystal), or when the input laser polarization was rotated by 90° , see inset of Fig.1(Left) (a),(b) respectively. Fig.1(Left) shows the measured pulse with risetime of ~ 70 ps and in dashed line is the instrument response to a ~ 15 ps laser pulse which shows that our measurement was bandwidth limited by the electronics.

The EO signal dependence on electron beam charge was investigated. The charge was measured using a Faraday cup and a stripline. The e⁻ beam was clearly passing below the EO crystal unobstructed. A linear χ^2 minimization fit to the signal amplitude for 5 charge values is shown in the inset of Fig.1(Right).

EO signal dependence on electron beam position was also investigated. Fig.1(Right) displays 5 signal amplitudes when the beam was steered vertically toward, but not

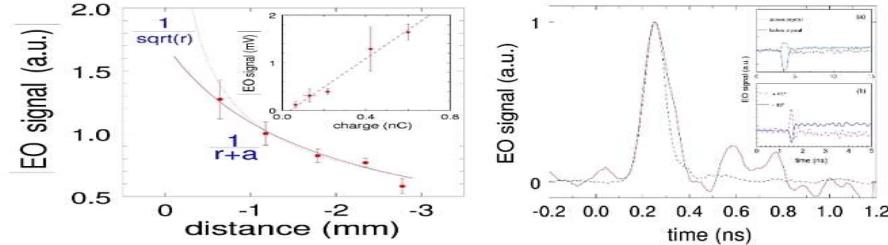


Figure 1: Left:EO signal(solid), instrument response(dashed) and polarity change(inset (a)and(b)); Right: EO signal amplitude vs distance and charge(inset).

traversing the crystal, versus their distance from the center of the laser beam path. A χ^2 minimization fit of the data favors a $\frac{1}{r+a}$ dependence, where $a = 1.75\text{mm}$.

As the electron beam approached the optical beam path a distinctive positive signal with a long ~ 100 ns decay time superimposed on the negative EO modulation was observed which becomes negative when tranverses the optical beam path. It is the electron beam that ionizes the LiNbO₃ crystal creating electron-hole pairs. Since the mobility of ions is small compared to the electrons, an ion field remains and produces an EO signal opposite to that due to the electron beam field. Its decay time will be dictated by the electron-hole recombination time of the crystal⁴.

4. Conclusions

The effectiveness of a Pockels cell field sensor has been demonstrated for nondestructive measurement of an ultrashort beam bunch. Using an upgraded pump-probe EO detection scheme and state-of-the-art ultrafast optical pulse measurement techniques such as frequency-resolved optical gating or spectral phase interferometry for direct electric-field reconstruction, femtosecond electron bunch may be studied. Furthermore, one can in principle construct a 2-dimensional EO detector array to measure the spatial and temporal profile of the charged particle beam bunch.

References

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